# Recent Advances in Phytoremediation Technology

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**Abstract**

The rapid increase in the environmental contaminants due to various anthropogenic activities has become a serious issue worldwide. New and efficient measures are explored to remove or contain the threat from the increasing levels of environmental pollution. Plant-based soil and water remediation (phytoremediation) is one such method which can prove to be a sustainable and promising treatment to remediate environmental problems. Phytoremediation exploits the abilities of green plants to uptake, stabilize, or metabolize the pollutants. Moreover, it is a cost-effective and environmentally safe approach as compared to conventional methods to solve the problems of soil and water pollution. Phytoremediation technique has been successfully applied to treat various contaminated sites and pollutants such as heavy metals, dyes, fly ash, hydrocarbons etc. and furthermore, research is underway for exploring new ways to improve the phytoremediation process.

**Keywords**

Environmental • Phytoremediation • Pollutants • Heavy metals

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## 14.1 Introduction

Rapid industrialization with increasing urbanization has enhanced the levels of contaminants in the environment and has become a serious global concern. Over the past few decades, there has been a considerable increase in the pollutants due to anthropogenic activities. Therefore, it is necessary to find new and efficient remediation methods to remove, reduce, or stabilize toxic substances introduced into the environment. Pollutants can be both organic and inorganic chemicals/compounds which include heavy metals as the major constituent of inorganic contaminants, xenobiotic compounds, hazardous wastes, explosives and petroleum products (Nikolić and Stevović 2015). These harmful compounds are toxic by nature and can enter the food chain causing mutagenicity and carcinogenicity in animals and human (Afzal et al. 2014). Therefore, their removal from soil and aquatic ecosystem is one of the important issues in the field of environmental sciences and engineering.

Traditional methods of soil remediation, such as liming, washing, leaching, turning and deep plowing, are usually energy-consuming and require expensive machinery that often causes secondary pollution. Conventional physical and chemical methods for the cleanup of soil and water polluted with organic compounds are often costly and environmentally destructive. Plant-based soil and water remediation (phytoremediation) is a sustainable and promising treatment that uses plants to remediate environmental problems. Moreover, phytoremediation is considered as a cost-effective and environmentally safe approach to conventional methods to solve the problems of soil and water pollution. Application of phytoremediation in cities is an attractive initiative to meet the prospects of the community (Table 14.1). Covering a contaminated site with vegetation creates open green spaces which have shown to reduce stress levels in people, improving their mental health, particularly in urban communities. These open green spaces have been recognized as physically, mentally and socially good for our communities, making them healthier (Nikolić and Stevović 2015).

Based on economic implications, phytoremediation may be focused on three major goals: (1) plant-based extraction of metals with commercial values, i.e., Ni; (2) risk minimization (phytostabilization); and (3) sustainable soil management in which phytoremediation steadily enhances soil fertility to boost up crop growth with increased economic value (Mahar et al. 2016).

## 14.2 Definition of Phytoremediation

Phytoremediation is defined as the use of plants to remove, metabolize, degrade and immobilize transferor detoxifying contaminants such as metals, hydrocarbons, dyes, and toxic substances from the soil, water, or air through their natural metabolic pathways and functions. Phytoremediation exploits the abilities of green plants to uptake pollutants. It is a promising new technology which is low cost, long term, environmentally, and aesthetically friendly.

**Table 14.1** Advantages and disadvantages of phytoremediation

| S. no. | Advantages | Disadvantages |
|---|---|---|
| 1. | Low investment cost and minimal equipment requirement (constitutes substantial savings) | Incomplete removal of pollutants with long-term low performance |
| 2. | Lower labor costs and reduced cost in operations | Limited applicability to different types of wastes, especially with high-level toxicity wastes |
| 3. | Can be applied in situ, i.e., on-site removal of contaminants, whether in the soil, water, or groundwater | Mainly applicable to the upper layer of the soil and mine tailings |
| 4. | Aesthetically pleasing and widely accepted to the public community | Proper disposal of plant matter is required with proper risk assessment |
| 5. | Nondestructive, nonintrusive, highly biologically active, therefore have very low environmental impact on soil and water | Possibility of introduction and spreading of undesirable invasive species of plants |
| 6. | Reduces erosion of soils, especially thinner inorganic soils | Effectiveness of the phytoremediation process is affected by seasonal factors |
| 7. | Reduces leaching of particulate matter and spreading of toxicants | Plant deaths may occur in highly toxic sites which could increase the cost of the process |
| 8. | Contaminants can be recovered from the plant tissues and offer opportunity for commercialization | Risk of bioaccumulation of pollutants in the food chain |
| 9. | Very effective at sites where low amount/ toxic contaminants are present | Good cultivation practices and maintenance are required to avoid accidents |
| 10. | Can be used for phytoremediation of soils that are nonproductive for agriculture | Better understanding of the behavior and physiological changes of plants in response to different types of wastes is needed |

Filippis (2015)

Over the past few decades, it has been recognized as a sustainable means of detoxifying contaminated soil and water sources. Historically, phytoremediation was first identified as a natural process and proved more than 300 years ago, and the first plant species discovered to treat sewage waste were *Thlaspi caerulescens* and *Viola calaminaria* (Nikolić and Stevović 2015). Phytoremediation can be applied to detoxify areas with trivial pollution of metal, nutrients, organic matter, or contaminants. It is emerging as an efficient technique with widespread application of different plant species in detoxification of various types of wastes (Table 14.2). With the discovery of new plants species having phytoremediation potential and better understanding of their metabolic pathways, phytoremediation could be the solution to the challenges of the twenty-first century.

**Table 14.2** Examples of plant species with phytoremediation potential

| S. no. | Plant species | Pollutants | References |
|---|---|---|---|
| 1. | *Cernuella virgata* | Zn, Cu, Mn, Fe | Nikolić and Stevovićc (2015) |
| 2. | *Chromolaena odorata* (L.) | Hg2+, radionuclide pollutants | Nikolić and Stevovićc (2015) |
| 3. | *Helianthus annuus* (L.) | Zn, Pb, Cd, Ni and Cu, As, radionuclides, especially U, xenobiotic | Nikolić and Stevovićc (2015) |
| 4. | *Brassica juncea* | Pb, Au | Mahar et al. (2016) |
| 5. | *Eleocharis acicularis* | Cu, Zn, Cd, As | Mahar et al. (2016) |
| 6. | *Nasturtium officinale* | Acid Blue 92 dye | Khandare and Govindwar (2015) |
| 7. | *Spartina maritima* | Ni, Zn | Curado et al. (2014) |
| 8. | *Momordica charantia* | Disperse red 17, Disperse brown 1 dyes | Tahir et al. (2015) |
| 9. | *Jatropha curcas* | POPs, heavy metals | Tripathi et al. (2016) |
| 10. | *Ricinus communis* | Cd, DDT | Tripathi et al. (2016) |
| 11. | Alfalfa (*Medicago sativa* L.) | TPH | Ndimele (2010) |
| 12. | Indian grass (*Sorghastrum nutans*) | TPH | Ndimele (2010) |
| 13. | *Sesuvium portulacastrum (L.)* L. | Reactive green 19A–HE4BD dye | Lokhande et al. (2015) |
| 14. | Sunflower | Endosulfan | Mitton et al. (2016) |
| 15. | *Cynara cardunculus* L. | Sewage sludge | Pandey et al. (2016) |

*Abbreviations: POPs* persistent organic pollutants, *DDT* dichlorodiphenyltrichloroethane, *TPH* total petroleum hydrocarbons

## 14.3 Phytoremediation Techniques

Phytoremediation can be classified into different categories/techniques on the basis of their mechanism (Fig. 14.1) such as (1) phytoextraction, (2) phytostabilization, (3) phytodegradation (phytotransformation), (4) phytovolatilization, and (5) rhizofiltration.

### 14.3.1 Phytoextraction

It is mainly used for accumulation of metals and involves plant root uptake of metals and their translocation through the xylem to the shoots and leaves, which are

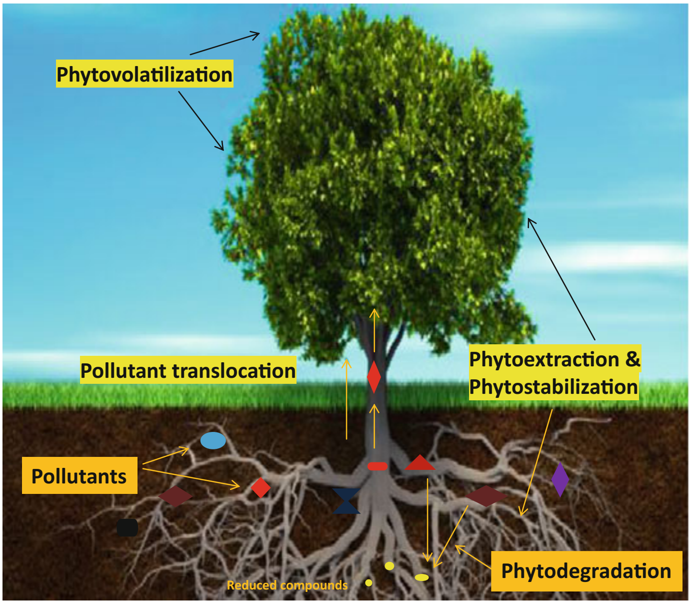


**Fig. 14.1** Types of phytoremediation

then harvested and subsequently removed from the site (Nikolić and Stevović 2015). This technology is an advanced form of phytoremediation in which high-biomass crops are grown in the contaminated areas and harvested to recover heavy metals. Thus, it can be commercialized by mineral industries to produce metals using bioharvesting. It is, therefore, also called as phytomining or biomining. This technique has several advantages as compared to conventional methods, i.e., it is cost-effective and reduces the erosion of soil as well. On the other hand, there are several factors that limit the potential of phytoextraction such as metal bioavailability within the rhizosphere, which depends on soil pH and clay content and cellular tolerance to toxic metals. Sunflower (*Helianthus annuus*) has been one of the most exploited species for phytoextraction, because of its fast growth, high biomass, and high potential in the remediation of certain heavy metals and other toxic compounds (Nikolić and Stevović 2015).

### 14.3.2 Phytostabilization

This approach mainly uses plant roots to immobilize and restrict contaminants in soil and groundwater through adsorption on roots or precipitation within the root zone (rhizosphere). The main role of phytostabilization is confiscation of contaminants in the rhizosphere, but not in the plant parts. This process prevents the pollutants from migrating to the groundwater, hence reducing their bioavailability into the food chain. Thus, the future adverse effects of pollutants in the surroundings can be controlled by restricting them from entering the groundwater or spreading in the air. This approach is useful at those contaminated sites where there is no available method for detoxification. It is a simple and cost-effective technique for stabilizing and reducing bioavailability of contaminants in the environment. However, the major disadvantage of this method is that contaminants are not removed from the soil and require a regular monitoring. Phytostabilization is a suitable technique to remediate Cd, Cu, As, Zn and Cr. In recent studies, perennial ryegrass (*Lolium perenne* L.) was observed as potential plant for the phytostabilization of mine-polluted soil and municipal solid waste compost and, to a lesser extent, sewage sludge (Nikolić and Stevović 2015).

### 14.3.3 Phytodegradation (Phytotransformation)

Phytodegradation includes plant metabolic system in association with microorganisms to detoxify heavy metals and organic pollutants such as herbicides, insecticides, chlorinated solvents and inorganic contaminants. It is also known as phytotransformation. In this approach, the pollutants are absorbed by plants and further broken down into insoluble and inert materials, which are either released as exudates or stored in lignin tissues. Pollutants can also be metabolized in the plant tissues with the help of enzyme-catalyzed metabolic process within plant root and/or shoot cells. The metabolic enzymes, e.g., dehydrogenases, oxygenases and reductases, transform pollutants into nutrients that can be utilized by the plants in their own metabolism. Contaminants thus are transformed, biochemically bounded to plant tissues, and become biologically less harmful to the environment (Nikolić and Stevović 2015).

### 14.3.4 Phytovolatilization

Phytovolatilization involves the use of green plants to absorb pollutants from contaminated sites, transform them into volatile compounds, and transpire them out through their aerial organs. It was observed in a study at USDA Agricultural Research Service that some plants are able to transform Se in the form of dimethylselenide and dimethyldiselenide in high-selenium media which can be transcribed out of the plants (Ahmadpour et al. 2015). Phytovolatilization has been used for contaminants like mercury (Hg); inorganic chemicals that have volatile forms, such as selenium (Se) and arsenic (As); as well as volatile organic compounds (VOCs), e.g., trichloroethene. The advantage of phytovolatilization is that toxic pollutant may be transformed into less toxic substance and then released into the atmosphere. However, the substance released into the atmosphere is likely to be recycled by precipitation and then redeposited into aquatic ecosystem, repeating the production of the toxic form of the substance (Nikolić and Stevović 2015).

### 14.3.5 Rhizofiltration

Rhizofiltration is the combination of phytoextraction and phytostabilization. This process involves absorption, concentration, and precipitation of contaminants in wastewater, surface water, or polluted groundwater by plant roots. The absorbed and concentrated pollutants are precipitated as carbonates and phosphates inside plant roots. Recently, it has been shown that hydroponically grown terrestrial plants, such as mustard and sunflower, effectively remove Cu, Cd, Cr, Ni, Pb, Zn and Fe from aqueous solutions. Besides metals, it was also observed that rhizofiltration can be used to remove organic compounds such as tetrachloroethane, trichloroethylene (TCE), metolachlor, atrazine, nitrotoluenesanilines, dioxins and various petroleum hydrocarbons. Terrestrial plants are more advantageous for rhizofiltration process due to their fibrous and much longer root systems. However, the plants need to be disposed regularly and harvested periodically which limits the scope of this rhizofiltration process (Nikolić and Stevović 2015).

## 14.4 Plant-Assisted Microbial Degradation

This phenomenon involves degradation of contaminants by microorganisms like bacteria and fungi which are present within the plant root zone or rhizosphere. The phytochemicals released by the plant roots, such as sugars, amino acids, enzymes and other compounds, are taken up by these microorganisms to enhance their metabolism and biological activity. In this way, plants accelerate biodegradation of contaminants by helping the soil microbes to flourish in their surroundings. These rhizosphere microorganisms can act directly on organic and inorganic pollutants through volatilization, transformation and rhizodegradation. For example, toxic metals like mercury (Hg) and selenium (Se) are phytovolatilized by microbial interactions with the plant. Furthermore, several bacterial species contain plasmids that have resistance genes to heavy metals and metalloids, e.g., $Ag^{+}$, $Cd^{2+}$, $Hg^{2+}$, $Ni^{2+}$ etc. which can be genetically altered to enhance the removal of these toxic metals. In addition, soil microbes prevent phytopathogens from infecting plants by increasing biomass production, which in turn make the plants much more efficacious in phytoremediation (Nikolić and Stevović 2015).

## 14.5 Endophytic Bacteria

Endophytic bacteria are generally found in all plant species and inhabit different plant tissues without conferring pathogenicity to the host. Some of these bacteria may have beneficial effects to their host plant by several mechanisms which are similar to rhizosphere bacteria. These endophytic bacteria produce several enzymes that help in degradation of various organic compounds present in the rhizosphere and endosphere of plants growing in polluted environments. Endophytes may have several advantages as compared to rhizosphere bacteria in regard to the degradation of xenobiotic compounds. They may degrade contaminants in both rhizosphere and endosphere as they are efficient colonizers of both the environments. Thus, they are likely to detoxify the plant environment more efficiently in such manner. Endophytes, in many cases, are efficient plant growth promoters and induce tolerance to abiotic stress in their host plants. Another significant advantage of endophytes is that the toxic compounds are degraded within the plant tissues, thus eliminating any toxic effects on herbivorous fauna residing on or near contaminated sites (Afzal et al. 2014). Several endophytes like *Enterobacter* sp. and *Pseudomonas putida* that have been isolated from common plants such as poplar (*Populus deltoides*) are able to degrade volatile organic compounds such as trichloroethylene (TCE).

## 14.6 Application of Phytoremediation

### 14.6.1 Role of Phytoremediation in Heavy Metal Removal

Heavy metals are considered as one of the most significant environmental pollutants that can have serious effects on soil and water quality, plant and animal growth, as well as human health. The generic term of "heavy metals" refers to elements that have metallic properties such as high specific gravity, density, conductivity, stability as cations, and an atomic number greater than 20 (Oosten and Albino 2014). For example, arsenic (As), cobalt (Co), chromium (Cr), silver (Ag), cadmium (Cd), copper (Cu), molybdenum (Mo), nickel (Ni), iron (Fe), mercury (Hg), manganese (Mn), lead (Pb) and zinc (Zn) are considered as heavy metals, also called as PTE (potential toxic elements).

Heavy metals enter the environment through two different ways that are from natural and anthropogenic sources. Natural sources constitute a little of the contribution, while anthropogenic activities such as mining, smelters, foundries, coal-fired thermal power plants, metal plating, tanneries and battery and paper industry are the major sources of the heavy metal contamination. Heavy metal contamination is a serious issue of global concern as these metals are persistent in the environment, unlike other organic material. Accumulation of these heavy metals in living organisms is of particular concern as these metals are carcinogenic and can bioaccumulate to higher toxic concentrations. Metal ions cause toxicity through the following mechanisms: (1) generation of reactive oxygen species (ROS) that reacts with antioxidants and cause oxidative stress; (2) direct interaction with proteins through affinity to different functional groups such as thionyl, histidyl, and carboxyl groups; and (3) displacement of essential cations in specific binding (Oosten and Albino 2014).

Therefore, there is an urgent need for the removal/stabilization of these heavy metals from the contaminated environment. Conventional methods are generally used but they have their own drawbacks. Phytoremediation can be used as an important alternative to the conventional strategies as it is cheap and eco-friendly. Most of the plant species have the ability to absorb/immobilize metals. There are certain woody or herbaceous plants that can accumulate and tolerate higher levels of heavy metals in their tissues and are known as hyperaccumulator (Ahmadpour et al. 2015). These naturally occurring hyperaccumulator plant species are suitable candidates for phytoremediation. A few examples of the hyperaccumulator plant species are *Aeolanthus biformifolius* (Cu), *Berkheya coddii* (Ni), *Euphorbia cheiradenia* (Pb), *Hordeum* spp. (Hg), *Pteris cretica* (As), etc. (Mahar et al. 2016).

### 14.6.2 Phytoremediation of Textile Dyes and Effluents

Application of dyes in a variety of industrial activities such as pulp and paper processing, paint and pigment manufacturing, leather tanning, and textile dyeing results in dumping of dye containing effluents into water pools and surrounding industrial areas, which subsequently affects ground and surface water resources and soil properties as well. Dyes are complex aromatic compounds that are used for coloration of fabrics, leathers, papers etc. Natural dyes are extracted from plant or animal sources, while dyes that are produced by chemical synthesis are called as synthetic dyes. During the process of dyeing, large proportions of these dyes remain unbound or unfixed, and therefore end up as effluents in sewage water or natural environment. It has been estimated that 10–15% of these dyes are released as effluents into the environment during textile dyeing, whereas unreactive dye losses of up to 50% have been reported. Dye-based effluents and/or wastewater usually have higher concentrations of suspended solids, while the presence of dyes in water bodies along with posing turbidity problems also causes an increase in BOD and COD levels. Moreover, chromophoric groups of dyes strongly absorb sunlight, thereby inhibiting the photosynthetic activity of phytoplanktons including aquatic plants and algal species by preventing light penetration (Tahir et al. 2015). Thus, apart from destroying natural quality of water bodies, these dyes also threaten aquatic biota such as flora and fauna by disturbing the ecological balance and posing serious environmental concerns and hence need to be treated or removed prior to their disposal or dispersal into water bodies or surrounding environment. Conventional strategies are not that much promising; instead, recent studies have shown that a great deal of plant species are able to metabolize, absorb, or detoxify various dyestuff and colorants. Plant species like *Brassica juncea*, *Rheum rhabarbarum*, *Tagetes patula*, *Thymus vulgaris*, *Rosmarinus officinalis*, *Phragmites australis*, *Rumex acetosa*, *Typha angustifolia*, *Hydrilla verticillata*, *Nasturtium officinale*, *Petunia grandiflora* Juss., *Glandularia pulchella*, *Armoracia rusticana* (horseradish), etc. have proved to be potential degrader of synthetic dyes. *Typhonium flagelliforme* was found to have significant dye degradation competency (67%) while *Chara vulgaris* displayed 95% decolorization of Congo red, whereas biotransformation rates of approximately 60% and 40% have been achieved in the case of *Momordica charantia* against Disperse Red 17 and Disperse Brown 1 dyes. A few other examples are *Z. angustifolia*, *Brassica juncea*, *Blumea malcolmii*

Hook.f., *T. patula* and *Hydrocotyle vulgaris* which have shown potential for the removal of textile effluents (Tahir et al. 2015).

### 14.6.3 Removal of Fly Ash

Coal-based thermal power plants produce an enormous amount of coal fly ash (600 million tonnes/year) and are a major constituent of the air and land pollution. India is one of the largest producers of fly ash (FA) with much of its energy requirement (approx. 80%) achieved by coal-based thermal power plants (TPP). The disposal of FA causes significant health and environmental hazards, and thus its disposal and utilization have become a worldwide concern. A total of only 30% of the global FA production is being utilized annually which is far less than required. Moreover, mobilization of its harmful constituents and airborne particulate matter and high amounts of toxic/heavy metals possess a great risk to the ecosystem (Ghosh et al. 2014).

Additionally, measures such as landfill cannot be considered as an eco-friendly alternative due to its high concentration of heavy metal content and the presence of radionuclides. Therefore, phytoremediation can be used as a practical, economical, and eco-friendly alternative for revegetation and reclamation of FA dump sites. A recent study has shown vetiver (*Vetiveria zizanioides*) grass system to be capable of remediating FA by stabilizing the metals in the root. Vetiver system is tolerant to extreme environment and capable of protecting the upper layer of soil. Besides phytostabilization of the heavy metals, vetiver also plays a role in reduction of genotoxicity caused by fly ash (Ghosh et al. 2014).

### 14.6.4 Phytodegradation of Oil Hydrocarbons

Oil spills are one of the main sources of aquatic contamination as a result of petroleum production, transportation, refining, and accidents. They are the major cause of disrupting the aquatic ecosystems throughout the world. Petroleum is highly toxic and can prove to be lethal to living organisms. The heavy fraction of the crude oil mostly contains naphthene–aromatics and poly-aromatic compounds which are carcinogenic, and if exposed for longer periods, these compounds may lead to tumors and failure of nervous system. (Abha and Singh 2012). It is estimated that nearly 8 million metric tonnes of crude oil are released in the aquatic environment every year. For example, the oil spill of North Slope into Prince William Sound, Alaska, from the Exxon Valdez, 1989, led to the death of thousands of seabirds and marine fauna and many long-term environmental effects. Another devastating spill occurred due to the explosion of Transocean Deepwater Horizon rig in 2010, killing 11 people and threatening coastal Louisiana, Gulf of Mexico, and surrounding ecosystems (Ndimele 2010). Conventional strategies for cleaning oil spills are various physicochemical methods such as booming and skimming, manual removal (wiping), water flushing, sediment relocation, and tiling. Apart from that, a range of bacteria, microscopic fungi, and yeasts are well-known degraders of oil hydrocarbons and are considered ecologically progressive approaches as compared to physicochemical treatments.

However, recent studies have observed that several species of plants have the ability to grow in the oil-contaminated sites and actually extract the contaminants from the area. A few examples are western wheatgrass (*Agropyron smithii*), prairie buffalo grass (*Buchlo dactyloides* var. prairie), soybean (*Glycine max*), etc. which have demonstrated potential to phytoremediate oil hydrocarbons. Grasses are considered to be superior candidates for phytoremediation as they have an extensive, fibrous root systems which can penetrate deep (3 m) in the soil. Water hyacinth (*Eichornia crassipes*) would also prove to be a promising agent for phytoremediation because it has fibrous root system like prairie grass system while it floats on the surface of the water. As most of the oil spills occur in the water bodies, an aquatic floating plant like water hyacinth is, therefore, of extreme importance. A recent study has shown that soybean (*Glycine max*) and sunflower (*Helianthus annuus*) could degrade motor oil from the soil-contaminated site (Ndimele 2010).

### 14.6.5 Phytoremediation of Landfills

The most common method of waste management practiced globally is disposal of waste to landfills with up to 95% of generated refuse dumped in landfill. Landfilling offers an easy and relatively inexpensive means of waste disposal; however, if not managed suitably, it can cause serious contamination of the surroundings due to release of various contaminants such as liquids, gases, or dust particles (Kim and Owens 2010). The major drawback concerning with landfill sites includes soil and groundwater contamination and gas emissions, which as a result have adverse effects on the human population as well as the plants surrounding the area. On the basis of waste disposed, landfill sites can be broadly categorized into three groups: (1) municipal waste, (2) industrial waste, or (3) a combination of municipal and industrial wastes. Municipal waste mostly contains a large range of organic waste, while industrial waste is composed of unknown components and may include certain toxic materials and heavy metal (Kim and Owens 2010). These components are leached subsequently from the landfill sites and can disrupt the surrounding ecosystem. Landfill gas is mainly composed of methane, carbon dioxide, carbon monoxide, oxygen, nitrogen, hydrogen and hydrogen sulfide in different proportions. The main components are methane and carbon dioxide, comprising between 40 and 60% of the total gas emissions from landfill and are considered harmful to the environment. Methane and carbon dioxide are well-established as greenhouse gases and contribute to global warming.

Recent studies have aimed at developing an alternative to the conventional engineering-based remediation methods, and phytoremediation has proved to be a promising technique as it has the advantages of being cost-effective, environmentally friendly, and less disruptive to the soil, thus maintaining the ecosystem. There are two different approaches that can be used for phytoremediation of landfill sites: (1) contaminant extraction/degradation and (2) stabilization. In the first approach, plants grown in heavy metal-contaminated sites can accumulate heavy metals into different plant tissues through their uptake mechanism which can further be harvested and removed from the site. The second approach involves the stabilization and prevention of runoff and dust blow to surrounding areas with the help of plant vegetation. Further, plants can prevent inorganic contaminants from leaching to groundwater by stabilizing them around the root zone. Trees growing on landfill caps can also promote favorable environments for methane-oxidizing bacteria, thus reducing its emissions from landfills.

In particular, communities in residential areas would be more attractive toward phytoremediation technologies due to the environmentally friendly nature of such systems.

### 14.6.6 Removal of Radioactive Waste

Radiation exists all around us, and the radioactive substances emitting these radiations are beneficial to humans and society in certain ways. For example, radiations are utilized in scientific, medical, agricultural, industrial and energy generation programs. Therefore it is inevitable that these diverse activities lead to generation of radioactive waste. Radioactive waste can be solid, liquid, or gas from various group of operations and activities (nuclear power and uranium mining) and accidents (spills and reactor meltdown), but irrespective of its origin, radioactivity poses a great risk to humans, the environment, and the ecosystems. However, at present, there are no established permanent repositories and storage facilities for the most dangerous high-level nuclear wastes from nuclear power plants. The radiation leak that occurred due to the nuclear accident at Chernobyl, Ukraine, alone is believed to have increased the risk of cancer to humans by 0.1% (Filippis 2015). Current practices for removal of radioactive-contaminated soils are mostly focused on "excavation and dump" or "encapsulation," neither of which removes the contaminant from the soil. Immobilization and extraction by physicochemical techniques are expensive and can only be applied for small areas, where rapid, complete decontamination is required and the contaminant is moved safely elsewhere (Filippis 2015).Therefore, the low-technology in situ approach of phytoremediation is attractive, as it offers partial site restoration, partial decontamination, preservation of ecosystem, and physical structure of soils and is low cost. Moreover, it offers the possibility of biorecovery of useful radioactive nuclides from the plants. Phytoremediation has become a fast growing field of research and development for application to radionuclide waste. In recent studies, three different grass species, namely, *Paspalum notatum*, *Sorghum halepense* and *Panicum virgatum*, have been used to accumulate 137Cs (100+8 Bq $g^{-1}$) and 90Sr (112 +7 Bq $g^{-1}$) in soil contaminated with these radionuclides. Other examples are *Amaranthus retroflexus*, *Brassica juncea and Phaseolus acutifolius* which have shown potential in removal of radioactive nuclides (Singh et al. 2008).

Phytoremediation, although still an emerging technology for radioactive contaminated sites, has the potential for greater industrial acceptance due to its low cost and environment-friendly approach.

## 14.7 Genetic Engineering to Improve Phytoremediation

Genetic engineering is the manipulation of the genetic makeup of an organism using biotechnological tools. It is one of the important techniques that can be employed to improve the phytoremediation potential of plant species to a greater extent. Biotechnological approaches (genetic engineering) can be used to insert one or more effective accumulator genes from taller plants into other smaller plants, and thus the final biomass can be increased. For example, genes responsible for metal-scavenging properties of hyperaccumulating plants, such as *T. caerulescens*, can be inserted into high-biomass generating species, such as Indian mustard (*Brassica juncea*) or maize (*Zea mays*) to enhance their phytoremediation potential for commercial utilization. Recent studies have shown successful utilization of genetic engineering to manipulate metal uptake and stress resistance properties in various species. One example is the enhanced metal resistance in tobacco (*Nicotiana tabacum*), achieved by expressing the mammalian metallothionein metal-binding proteins. Currently, transgenic plant species are being produced using genetic engineering and are employed in phytoremediation of soil contaminated with methyl mercury (a neurotoxic agent). Transgenic tobacco and *Arabidopsis* are a few examples which express bacterial genes *merB* and *merA* and have the potential to remove mercury from the soil. The *merB* gene present in these transgenic plants carry out protonolysis of the carbon–mercury bond and thus liberate $Hg^{2+}$, a reduced mobile mercury species, and the *merA* gene converts $Hg^{2+}$ to $Hg^0$ (elemental Hg) which is a less toxic, volatile element and is liberated into the atmosphere (Malik et al. 2015). Genetic engineering can also be applied to the bacteria assisting plants in phytoremediation. In these bacteria, genes may be inserted for biodegradative enzymes, biotic and abiotic stress, metal uptake regulators and risk mitigation which, in turn, enhance phytoremediation. One such example is expression of phytochelatin synthase (PCS) genes from *Schizosaccharomyces pombe* into *Pseudomonas putida* KT2440 which resulted in recombinant strain KT2440-*spPCS* with increased resistance to Hg, Cd and Ag and a 3–5-fold increase in Cd accumulation, hence increasing the efficiency of phytoremediation (Yong et al. 2013).

These studies reveal that genetic engineering has a tremendous potential in increasing phytoremediation opportunities for different plant species.

## 14.8 Challenges for Phytoremediation

There are several challenges that need to be overcome to increase the use of phytoremediation for waste treatment. A few are listed below:

- Longer period (several years) required for remediation process.
- Phytoextraction efficiency of most of the hyperaccumulator plants is usually limited due to their low-biomass production and restricted growth rate.
- Climatic factors affect the accumulation capacity of some plants and in some cases, pests and disease can hinder the phytoremediation process.
- Invasiveness of some of the hyperaccumulator plant species which affect the indigenous flora diversity.
- Accumulation of pollutants into food chain if not handled carefully (Mahar et al. 2016).

## 14.9 Conclusion and Future Prospects

Environmental contamination is a serious global concern, and therefore efficient and economical remediation alternatives are necessary. Phytoremediation is an attractive approach with good community acceptance. It is an eco-friendly and solar-driven technology which is cost-effective and offers opportunity for its commercialization as well. At present, phytoremediation technology is in its early stages, and there are many technical problems that are needed to be addressed for its development. However, advancements in genetic engineering and development of innovative agronomic practices would greatly help this technique to be more effective and relatively simple. Besides that, there is an urgent need to discover and explore new hyperaccumulator plant species for their potential and mechanism of phytoremediation. A thorough research is required for the optimization of processes, understanding the dynamics of plant–pollutant interactions, plant–microbe interactions and means of proper disposal of waste with minimum damage to the environment. The role of various additives and other factors that influence the phytoremediation process is still needed to be explored. Moreover, the use of applied molecular techniques and development of transgenic plant with enhanced phytoremediation activity are gaining widespread acceptance; therefore, genetic engineering is expected to play an important role in boosting the applicability of phytoremediation technologies. Studies concerning these strategies would be very helpful in the development of easier and cost-effective tools for phytoremediation.

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